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DONAR: An Instrument System for Digitizing Ultrashort Sonic Wave Trains

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DONAR: An Instrument System for Digitizing Ultrashort Sonic Wave Trains

There are many instances where it is beneficial to be able to manipulate the signals obtained from ultrasonic sources. In this study only signals arising from pulse echo systems are discussed but the same concepts should be applicable in other ultrasonic systems. The ultrasonic signals are treated intact with all possible fidelity.

A general purpose instrument with the name DONAR that can readily treat all applications based on a digital computer has been designed and installed. DONAR can be programmed to run an experiment, record the data in digital form, extract desired information, process the data and display the new form of the information or plot the data. It can be readily instructed to change the operating conditions to suit the problem in hand. The advantages of DONAR over analog techniques will be discussed presently.

Characteristics Underlying the Design

The major characteristics of a pulse echo system in many physical situations, especially for biological applications are:

1. The sonic pulse duration is quite short, usually one microsecond or less;
2. The target moves slowly or not at all;
3. The echo pattern returns after a delay of microseconds;

4. The repetition rate of the pulsed emission is adjusted so that the time between pulses must be much longer than the echo pattern including the initial delay.

Since the target moves slowly a sampled data approach is feasible. The pulse echo pattern is generated at a high repetition rate which still permits a sampled digitized value to be extracted each cycle and the complete pattern can be sampled before a detectable displacement of the target is evident. Even at a repetition rate of 10,000 Hz there is a 100 microseconds between samples, which is ample time to reset the system for the next sampling sequence.

<u>The Information Bandwidth</u>

The sonic carrier is characterized by a large frequency bandwidth, as much as 30 mHz or more, depending on the application, while the target motion bandwidth seldom exceeds 10 Hz. It is useful to consider the consequences, from an informational viewpoint, of this large difference in bandwidth between the sonic carrier and the information it conveys. Pulse echo systems are often used to measure the distance between two surfaces in the target. The information is the distance between the surfaces but the ultrasound is the means for carrying the information; the sound is not the information.

The first advantage of digital representation of ultrashort sonic wave trains is its capability to strip information from the carrier. Once the information is stored it is no longer necessary to consider the sonic carrier bandwidth as a constraint on the information process.

Let d be the distance between surfaces and c the sonic velocity in the propogating medium. If the uncertainty in the target range is not to exceed δ, the equivalent uncertainty in time is

$$t = \delta/c$$

and the minimum sonic carrier bandwidth is

$$f_{s(min)} = 1/\ \Delta t = c/\delta$$

On the other hand if the target motion requires an interval $\Delta\tau$ to generate a displacement, δ , and if

$$\Delta\tau \gg \Delta t$$

then

$$f_d = \frac{1}{\Delta\tau} \ll f_{s(min)}$$

Since a major source of uncertainty is ascribable to Johnson noise given by

$$e_j = 10^{-11} \quad \sqrt{fRT} \qquad \text{volts (RMS)}$$

where f = bandwidth, R = resistance and T = Kelvin temperature, the Johnson noise limit for information about the target with bandwidth 10 Hz is at least three orders of magnitude less than for the sonic carrier with bandwidth 10 mHz. If the target is quasistationary, as it is for many applications, the information bandwidth approaches zero as does the associated Johnson noise. The residual uncertainties are all that remain, such as that associated with the sampling process.

DONAR provides the option of repeating the sampling process many times. Presumably a simple time average should reduce the uncertainty due to Johnson noise to within any desired level approaching that of the information bandwidth. At this time the system is designed to provide a choice of 1000 or 10,000 pulses per second. The higher repetition rate is used with near targets. Experience with the system indicates that in 50 repetitions the noise is reduced to a level that appears to be associated with the sampling process rather than to Johnson noise. At this point it is possible to use analytical smoothing techniques to increase the signal to noise ratio. The technique presently being employed is that devised by Savitsky and Golay (1). A 25 point sliding cubic is used to smooth the data in accordance with the procedure described in the reference.

DONAR as an Amplifier

A second advantage of DONAR is to use it as a low noise amplifier. As successive repetitions are added to each point the magnitude increases. While the noise tends to average to zero the signal becomes cumulatively larger. It is a consequence of the tremendous available bandwidth reduction that makes it possible to use the computer as a low noise amplifier. The information carried by the sonic wave train does not vary significantly in time and the redundancy in repeated observations reduces the uncertainty. The computer serves as an amplifier in a second way. When the signal is digitized, the voltage level of the digital representation bears no relationship to the voltage of the signal itself. It is the coded form of the digitized message that specifies the signal voltage. The digitized quantity can be used to control a much larger output than original signal without analog amplification such as is needed to drive a scope display, a digital printout or an x-y recorder. This advantage of digitized signals has long been known.

DONAR is a Differential Amplifier

A major use of DONAR is to employ it as a kind of differential amplifier. The system stores the echo signal pattern in digital form. An echo pattern is obtained and stored when the target is absent. With the same acoustical load, the target is presented and a second echo pattern is stored. The difference between the two should eliminate any interfering background and the resultant difference pattern represents the echoes pertaining only to the target. The computer system functions as a differential amplifier where the transducer is used as its own reference. It is difficult to fabricate two identical transducers for use with a conventional differential amplifier where the computer provides a relatively simple means for accomplishing the task. Most of the applications employ the differential amplifier capability.

DONAR as a Time Gating Amplifier

It will be explained subsequently how the system is structured to sample the signal pattern over a desired time span. The computer can be programmed to provide samples over two or more distinct time spans if desired. In essence, therefore, the computer can be used to gate the signals. This is an inherent capability of the system. Variations can be employed which increase the number of sweeps in a limited range so that the equivalent of controlled gain can be effected for enhancing weak signals.

Data Retrieval and Presentations

A fifth advantage is the ease in retrieving data. It has proved useful to call up earlier experiments for comparison with current data or to reevaluate old data in the light of new information. Data is stored on magnetic tape for retrieval.

Finally it is advantageous to present the data in a variety of ways. With the inherent retrieval capability the data can be presented in any number of ways and compared with previously used methods. The same data can be shown in A-scan or B-scan or in alternate methods. The whole pattern can be examined or only a small part. The magnification can be changed at will and various smoothing routines can be employed. Data can be plotted to provide hard copy.

The six advantages of DONAR indicate its versatility which accrue in addition to the original advantage that the system can serve as a general purpose instrument with the capability of solving a wide variety of problems. The only limitation is the capacity of its core.

Other Digitizng Systems

A system somewhat like DONAR was described by Amsel and Bosshard (2) for application to the analysis of fast random signals. Freese (3) described a signal averaging system based on an ultrasonic input that has many of the basic concepts employed here, but his equipment does not have the resolution capability of DONAR, or much of its flexibility. His system was designed for a specific application. Commercial equipment has become available recently that converts a single transient to digital form, but this equipment is still unable to treat wave trains as short as those used with DONAR. Moreover, the technique used by this class of instruments does not provide samples at prescribed instants nor are the sampled points repeatable. It does not appear feasible to use such an instrument in the way described above as DONAR is employed. For example, it does not appear possible to reduce the uncertainty by repetition.

Structural Design

The structural design of the DONAR system is shown in Figure 1. The major subsystems are outlined by dashed line boxes with signal flow lines between subsystems. The central unit is the COMPUTER which in this embodiment is the Digital Equipment Co. PDP 9/L. The computer uses 18 bit words and is equipped with a 24 thousand word memory which is overlarge for most applications but provides a freedom from program length limitations and data storage capability. Operations are initiated and directed from the COMMAND subsystem usually by instruction from the teletype console. Programs are generally loaded from the tape decks but occasionally the punched tape reader is used. Certain other commands are given from a set of push buttons working together with the computer console entry keys which load the input register. The operating and display programs respond to these latter commands to initiate various desired functions.

Experience has demonstrated that best performance obtains when the SONIC subsystem operates at a constant frequency. A quartz crystal oscillator operating at 20 mHz serves as the master clock. An appropriate modulus is transmitted to a register in the sampling rate countdown timer in the REPETITION RATE GENERATOR. Pulses at the 20 mHz rate are counted down until the timer counter is zero at which instant a sampling start signal is sent to the DELAY GENERATOR. This subsystem in turn transmits an initiation pulse to the SONIC subsystem and at a later time emits an enabling signal to the SAMPLER.

The sonic echo signal is supplied to the SAMPLER through a coupling amplifier which serves to buffer the impedance mismatch between the transducer and the SAMPLER. When the delayed sampling control signal is received by the SAMPLER, the sampling bridge operates for 325 picoseconds, the duration of the sampling time window. The sampled signal is retained by the hold amplifier while the analog-to-digital converter transforms the sampled signal to digital form to be stored in the computer memory.

Sampling Subsystems

The SAMPLER DELAY GENERATOR and the SAMPLER are part of the Tektronix Sampling Oscilloscope Type R561 B with Type 3T2 Time Base plug in, Type 3S2 Sampling Unit plug in and Type S-1 Sampling Head. The choice of these units was based on considerations designed to minimize time jitter and noise consistent with the sonic wave train characteristics. The most critical component is the Sampling Head, since the Type S-1 has a DC to 1GHz bandwidth and a displayed noise less than 2mV unsmoothed.

The input impedance is 50 ohms. The other Tektronix sampling heads have wider bandwidths and more noise. The time jitter is less than 50 psec under the operating conditions.

Delay Generator -- Conceptual Considerations

The key to the system's performance is the operation of the DELAY GENERATOR since this subsystem controls the sampling procedure. Once the information is stored in the computer well known procedures are available for processing the data. The important consideration is to ensure precisely reproducible sampling times with respect to the launching of the sonic pulse. If the time for obtaining a particular point should vary from one sampling to the next, the data will be smeared and the desired information may be irretrievable.

An explanation of the design concept underlying the DELAY GENERATOR can be understood from an examination of the sonic wave train shown in Figure 2a where a complete sonic pattern begins with the emitted sonic pulse. For illustrative purposes an echo pattern is shown 12 microseconds after the emitted sonic pulse. The usual sonic image corresponds to Figure 2b where a delay has been introduced between the emitted pulse and the echo. The DELAY GENERATOR must provide a delay beginning the instant the transducer is excited and terminating at the instant of sampling.

It is convenient to generate the delay in two parts as illustrated in Figure 3, a course and a fine delay. These are developed under programmable control from teletype input commands before a test is performed. The cycle begins with a sampling start signal from the REPETITION RATE GENERATOR which causes the transducer to be excited and simultaneously actuates the COARSE DELAY COUNTDOWN TIMER. At the end of a preset number of counts of 50 nsec intervals a triggering signal is passed to the SAMPLER DELAY GENERATOR to begin the fine delay. At the end of the total delay a sampling control signal causes the sampling bridge to operate and the time window is opened for the input signal. During the remainder of the sampling cycle the A/D converter generates a 12 bit number corresponding to the sample voltage to be stored in the appropriate location of the computer memory and the computer resets the system to its initial state.

In the next cycle the process is the same except that the delay is advanced one increment of the fine delay. The sequence of samples is shown in Figure 3, where the upper drawing shows the timing of successive samples and the lower shows the sampled pattern. It is evident that the sample density must be sufficient to delineate all details of interest. It may be noted in Figure 3 that the second undershoot is lost because the sampling is too coarse.

Delay Generator -- Details

A more detailed view of the DELAY GENERATOR is shown in Figure 4 where the components of the SAMPLER DELAY GENERATOR may be seen. The COARSE DELAY TIMER receives three sets of signals: a sampling start signal to begin the countdown; a digital coarse delay signal from the computer which determines the duration of the coarse delay; and 20 mHz pulses from the 20 mHz clock which define the 50 nsec intervals that are counted. The component counts down to zero from the preset number.

At the end of the countdown a pulse is emitted to initiate a ramp voltage by the ramp generator, which is part of the Type 372 Time Base plug in. A variety of ramp voltages can be selected but the fastest one available is that which develops 15 volts in 100 nsec. The precise instant in determining when to open the time window falls on the computer which matches the delay reference voltage to the ramp voltage. Uncertainty is minimized by using the fastest rising ramp.

The computer provides the digital fine delay signal to the register in the 12 bit D/A converter whose output is a delay reference voltage level. The voltage level is generated anew each sampling cycle When the ramp voltage equals the delay reference voltage the comparator emits a signal to cause the sampler bridge to open and the sample is taken.

Determination of the instant the sampler bridge should open is under program control through the digital coarse delay and the digital fine delay signals. The final stage of the delay generation process depends upon matching a particular value of the ramp voltage. To ensure linearity of the intervals between samples as well as coincidence of successive coarse delay intervals, only the middle half of the ramp voltage is used, namely the 50 nsec portion beginning 25 nsec and terminating

75 nsec after the start of the ramp. It was this criterion that dictated the choice of 20 mHz as the clock frequency. The 50 nsec interval can be divided into 1000 equal subintervals by selection of delay reference voltages, so that the minimum time between sample points is 50 psec. Longer intervals between samples, in units of 50 psec, can be obtained by input at the teletype. The first sample is determined by inserting the appropriate digital multiple of 50 nsec which determines the initial value of the coarse delay.

Subsequent to the initial coarse delay the signal is sampled at successive values of the fine delay until 50 nsec have been traversed. The program adds an additional 50 nsec to the coarse delay and the process is repeated until the signal has been sampled over the entire allowable time interval. The program has been written to allow for the collections of 1000 samples. The actual signal time interval depends on the duration between samples. The minimum intersample duration is 50 psec, the maximum is 25 nsec so that for 1000 sampled values at least 50 nsec of the signal and a maximum of 25 microseconds can be viewed. The initial delay can be increased to 200 microseconds if required.

Operating Programs

Operating programs for DONAR are being revised as the project continues. However, certain features have been retained during the revisions. At this time two types of programs are employed, one for taking data and a second for evaluation with the tabulated options.

DATA ACQUISITION OPTIONS

1. Initial delay (in 50 nsec units)
2. Interval between samples (in 50 psec units)
3. Number of sampled points (1000 max)
4. Sampling rate (usually 1000 or 10,000 Hz)
5. Number of sweeps per test
6. Manual or automatic magnetic tape recording
7. Time interval between automatic magnetic tape recordings
8. Horizontal scale in nsec/ division
9. Vertical scale in mv/division
10. Attenuation.

In addition there are operational choices for the manual mode, available from push buttons. One button commands data to be stored positively while a second has the data stored negatively. A third restores the storage buffer to zero. This combination of commands permits the buffer to be zeroed, the target data to be accumulated and the reference data to be subtracted. At each step the status of the storage buffer is displayed either in storage or refreshed mode to permit the operator to guide the experiment. The program options can be changed at any time during manual operation but only at the start for automatic recording.

Further options are being added. It has proved useful to use more than one transducer at a time so multiplexing capability has been added. Certain experiments require a constant temperature and a digital multimeter now provides data that is recorded in addition to other information. Multiplexing is available for the digital multimeter which permits a variety of operating conditions to be recorded. It is intended to provide an option that in effect lengthens the duration of the signal being recorded without sacrificing desired detail. In this option it is presumed there are two regions of interest and the time between them can be deleted.

The capability to use many sweeps per test is important to minimize uncertainty as well as to use the computer as an amplifier. Although it has never been tried it is possible to employ several thousand sweeps per test. The danger is that there may be overflow in the register. However, fifty and a hundred sweeps per test are frequently used to reduce uncertainty.

The data evaluation programs are to be used with recorded data. In many applications the display available from the data acquisition program is adequate but there are other applications, particularly for determination of material properties where more detailed evaluation is necessary.

DATA EVALUATION OPTIONS

1. Smooth data, zero baseline and adjust amplitude to a selected reference.
2. Display recordings individually on command, or in automatic sequence

3. Display difference between one record as reference and any other
4. Present raw or smoothed data
5. Print raw or smoothed data, or difference between reference and other data sets
6. Plot curves on external plotter
7. Print parameters defining data acquisition options
8. Print critical values of selected parts of a curve such as zero crossing, maxima and minima.
9. Change horizontal and vertical scales, or attenuation
10. Expand selected regions.

These options provide additional flexibility in treating and presenting the data beyond that in the acquisition stage. The evaluation program is particularly useful in recalling previous experimental information for subsequent examination.

Examples of Performance

Some of the capability of the DONAR system may be illustrated by a few examples. In these examples the transducer was a one mm diameter PZT disc backed by bismuth alloy (Cerrobend 158). The thickness of the PZT disc corresponded to 8 mHz but the damped pulse length corresponds to 5 mHz, a behavior that is characteristic of well damped systems. The diameter is so small the low frequency mode (often called the radial mode) is close in frequency to the thickness mode and cannot be suppressed readily by filtering. Moreover, shock type excitation excites many different modes both higher and lower in frequency than that of the thickness mode as is evident in Fig. 7. At first sight it would appear that the transducer is in fact not damped at all.

However, the thickness mode is propagated in the conducting medium where the other excited modes appear only in the electrical output. In these applications DONAR is used as a differential amplifier with the transducer as its own reference. A target is exposed to the transducer in the coupling medium, which was water in this instance. The echo pattern is sampled and stored in the computer memory. The target is then removed and a second echo pattern is obtained using the same loading on the transducer. The difference between the two records is the echo pattern of the target.

In the first example it is demonstrated that the pulse is well damped. It also furnishes the opportunity to examine the wave form from the bismuth alloy backed transducer. Fig. 4a shows the echo pattern obtained from an aluminum plate before differencing while Fig. 4b shows the result after taking the difference. The echo is 60 mv peak to peak and is about 200 nsec in duration.

In the next example, Fig. 5, the target was a lucite plate 1.67 mm thick. The original echo can be seen in the upper figure, while the lower one shows the difference pattern. It is very evident that the transducer was well damped and that only the thickness mode wave was propagated. The low frequency wave pattern in the upper figure is an interference present only in the transducer and does not propagate into the water; otherwise there would be echoes from the target and the differencing procedure would not remove it. An additional amplifer was used to augment the echoes.

Determination of Dimensions of a Small Diameter Plastic Tube

An important problem is to determine the diameter and wall thickness of blood vessels. The next example shows how well a plastic tube in water can be measured taking this structure as a model for a blood vessel in tissue. In this example the four surfaces of the plastic tube are detected. A piece of PVC tubing was measured mechanically and found to have a diameter of 2.4 to 2.5 mm OD. The wall thickness was 0.4 mm as shown in Fig. 6.

The original echo pattern seen in Fig. 7, which exhibits a complex pattern indeed, becomes completely intelligible when the interference is subtracted and the result presented in Fig. 8. The four surfaces of the tubing can be instantly identified. From the figure it was determined that the interval between the inner walls was 2.24 microseconds corresponding to 1.68 mm. The tests were repeated to obtain echo patterns for the near and far walls on an expanded scale as shown in Fig. 10a and 10b. There is a third echo on the right in Fig. 10b which probably came from the plate under the tube.

The time lapse between corresponding points of the echo for the near wall was 400 nsecs and for the far wall 420 nsecs. This observation has been consistently observed. It is inferred that there is some distortion of the wave pattern due to the severe curvature of the plastic tube. Assuming the sonic velocity in plastic to be 2mm/ microsec., the wall thickness was found to be 0.4 mm by the ultrasonic test, corresponding to the mechanical measurement. The outside diameter of the tube was therefore found to be 2.48 mm by ultrasound. This demonstrates that it is possible to measure the thickness to within 0.1 mm. The uncertainty is probably much smaller but it would be presumptious to assert a smaller uncertainty at this time by such measurement techniques.

Locating an Edge

In the next experiment it is demonstrated that an edge can be located to within 0.1 mm. A piece of brass shim stock was cemented to a steel base so that part of the steel is exposed. As shown in Fig. 10 the brass shim as cemented on the steel plate was 0.31 mm above the steel surface. The transducer was mounted on an adjustable stage that permits both x and y displacements and it was oriented so that the transducer could be moved along a line perpendicular to the brass edge. In this way the transducer could be brought across the edge in successive steps and the change in the echo pattern observed. In the experiment the transducer was displaced by 0.1 mm steps. Initially the transducer was located over the exposed part of the steel base and a reference pattern stored in memory. At each 0.1 mm step the reference pattern was subtracted from the associated echo pattern and then the reference pattern was restored. In this manner a succession of echo patterns was obtained corresponding to each 0.1 mm increment.

The three echograms of Fig. 11 typify the changing pattern. The first was obtained when the transducer just began to encounter the brass edge; the second when the transducer was half way over the edge; and the third when the transducer was entirely over the brass.

The right echo corresponds to the echo from the steel plate while the left one is caused by the brass. The complete set shows the brass echo increasing in size from zero to the maximum The steel echo also increases because less is being subtracted from the reference at each step. The peak to peak magnitude of the brass echo is plotted in Fig. 12. There is a certain amount of waviness in the curve going through the points which is assumed to be due to the peculiarities of the field patterns and the response characteristics of the transducer. A straight dashed line has been drawn through the curve to indicate a linear approximation. The lower end of the curve shows no measurements because the echoes were too small to be able to assign values even though there was evidence of a change in the pattern. The straight line indicates that the transducer sensed the edge over a range of 1.2 mm which is about the diameter of the nominally one mm transducer. The midpoint of the pattern, presumably the location of the edge, can be determined to at least 0.1 mm.

Acknowledgement

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3. Freese, M. "Ultrasonic Inspection of Parasitized Whole Fish" FAO paper FE: FIC/69/0/12 21 May 1969.

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Figures

Fig. 1	Functional Diagram of DONAR
Fig. 2a	Delay Between Emitted Pulse and Echo
Fib. 2b	Sampling Pattern for Idealized Echo
Fig. 3	Scheme for Generating the Delay
Fig. 4a	Original echo from an aluminum plate using a one mm diameter PZT transducer
Fib. 4b	The difference pattern showing the well damped sonic pulse emitted by the transducer
Fig. 5	Echo pattern from a lucite plate 1.67 mm thick. Upper figure is the echo pattern before and the lower figure after differencing.
Fig. 6	Cross section of plastic tube showing mechanical measurements.
Fig. 7	Original echo from plastic tube
Fig. 8	The difference pattern showing echoes from four surfaces of the plastic tube of Fig. 6
Fig. 9a	Echo pattern from the near wall of the plastic tube
Fig. 9b	Echo pattern from the far wall of the plastic tube
Fig. 10	Brass shim mounted on a steel plate
Fig. 11	Echograms from brass shim mounted on steel plate
Fig. 12	Magnitude of brass echo as a function of displacement (arbitrary magnitude units).

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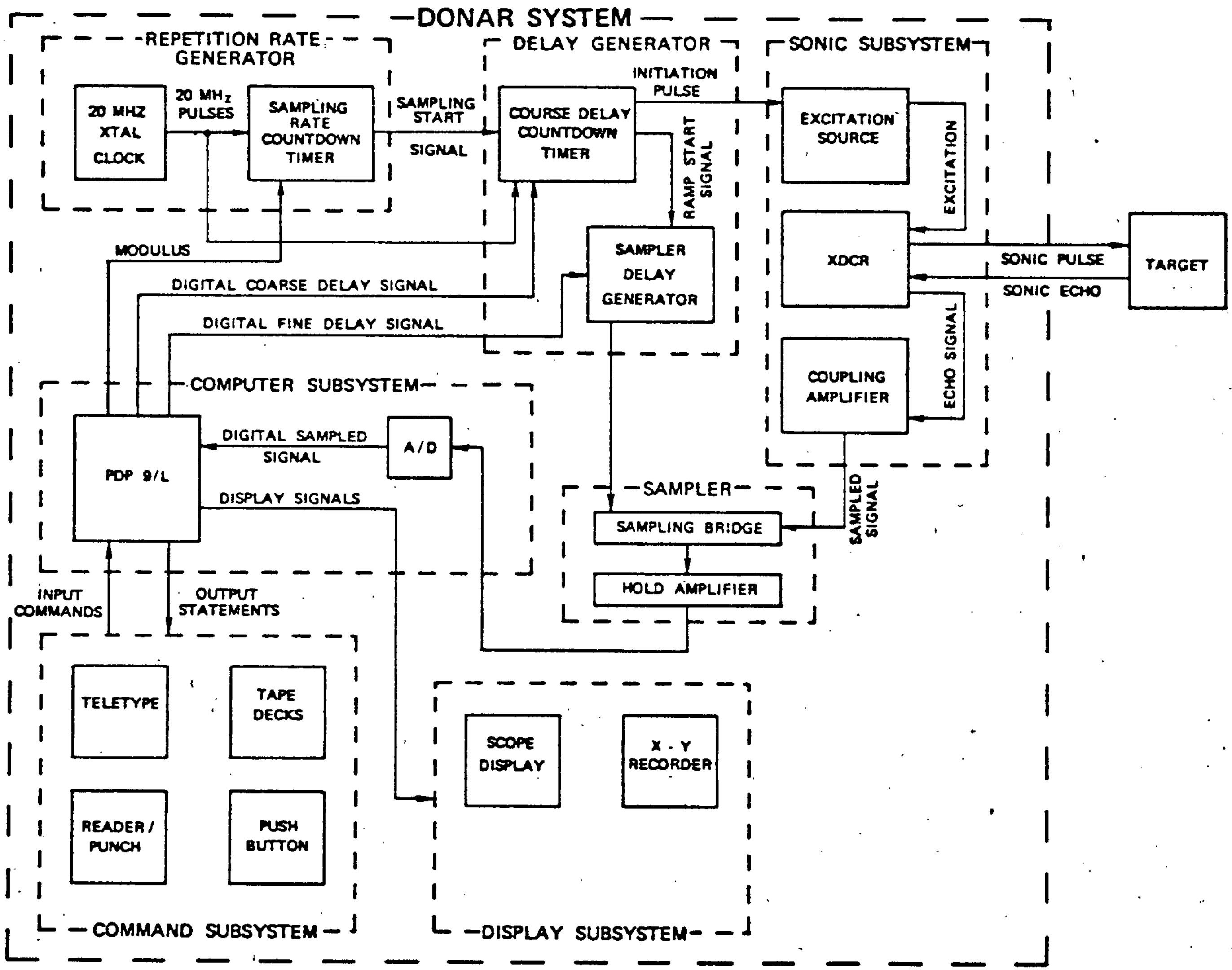
Fig 1



DONAR SYSTEM
REPETITION RATE GENERATOR
20 MHZ XTAL CLOCK
20 MHz PULSES
SAMPLING RATE COUNTDOWN TIMER
SAMPLING START SIGNAL
DELAY GENERATOR
INITIATION PULSE
COURSE DELAY COUNTDOWN TIMER
RAMP START SIGNAL
SAMPLER DELAY GENERATOR
SONIC SUBSYSTEM
EXCITATION SOURCE
EXCITATION
XDCR
SONIC PULSE
SONIC ECHO
TARGET
COUPLING AMPLIFIER
ECHO SIGNAL
MODULUS
DIGITAL COARSE DELAY SIGNAL
DIGITAL FINE DELAY SIGNAL
COMPUTER SUBSYSTEM
PDP 9/L
DIGITAL SAMPLED SIGNAL
A/D
DISPLAY SIGNALS
SAMPLER
SAMPLING BRIDGE
HOLD AMPLIFIER
SAMPLED SIGNAL
INPUT COMMANDS
OUTPUT STATEMENTS
TELETYPE
TAPE DECKS
READER / PUNCH
PUSH BUTTON
COMMAND SUBSYSTEM
SCOPE DISPLAY
X - Y RECORDER
DISPLAY SUBSYSTEM

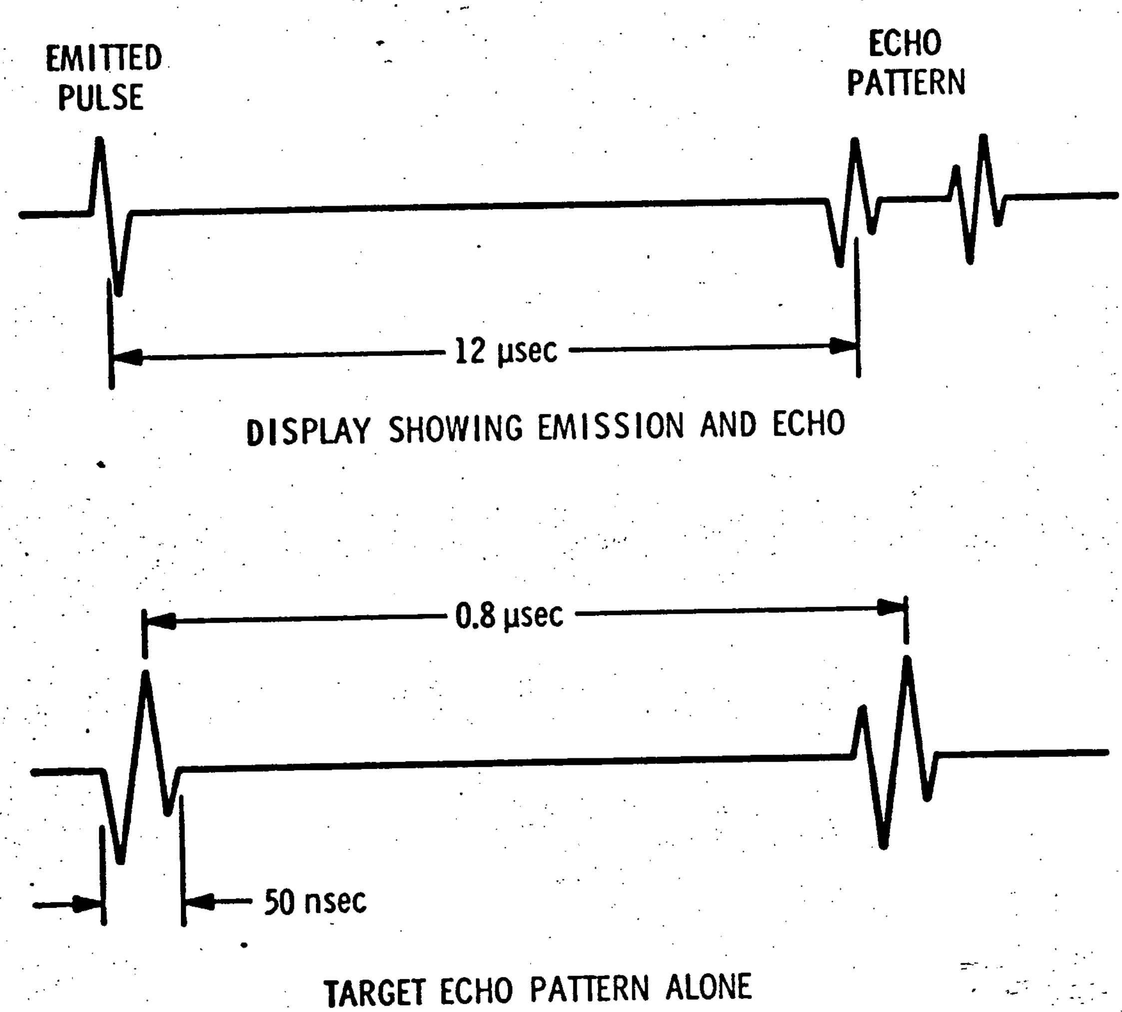


Fig 2a DELAY BETWEEN EMITTED PULSE and ECHO

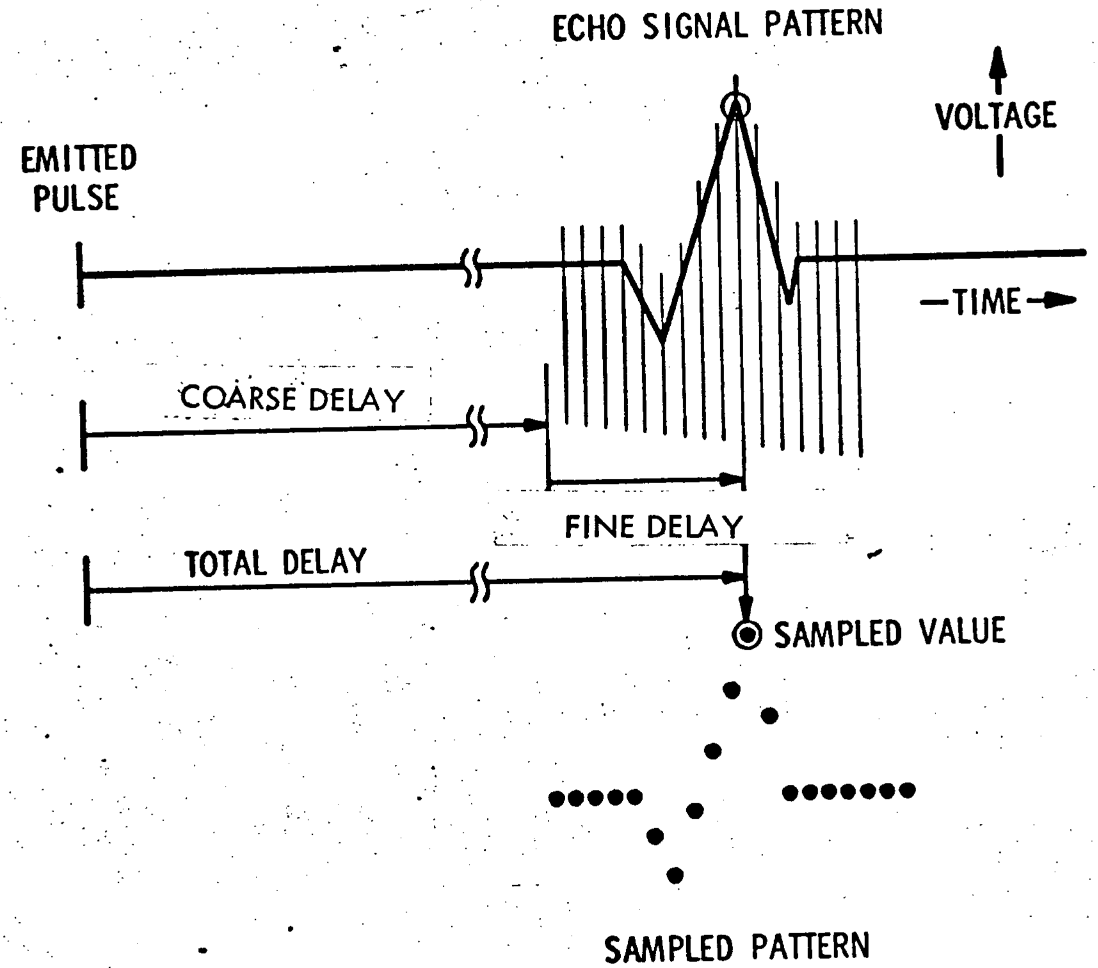
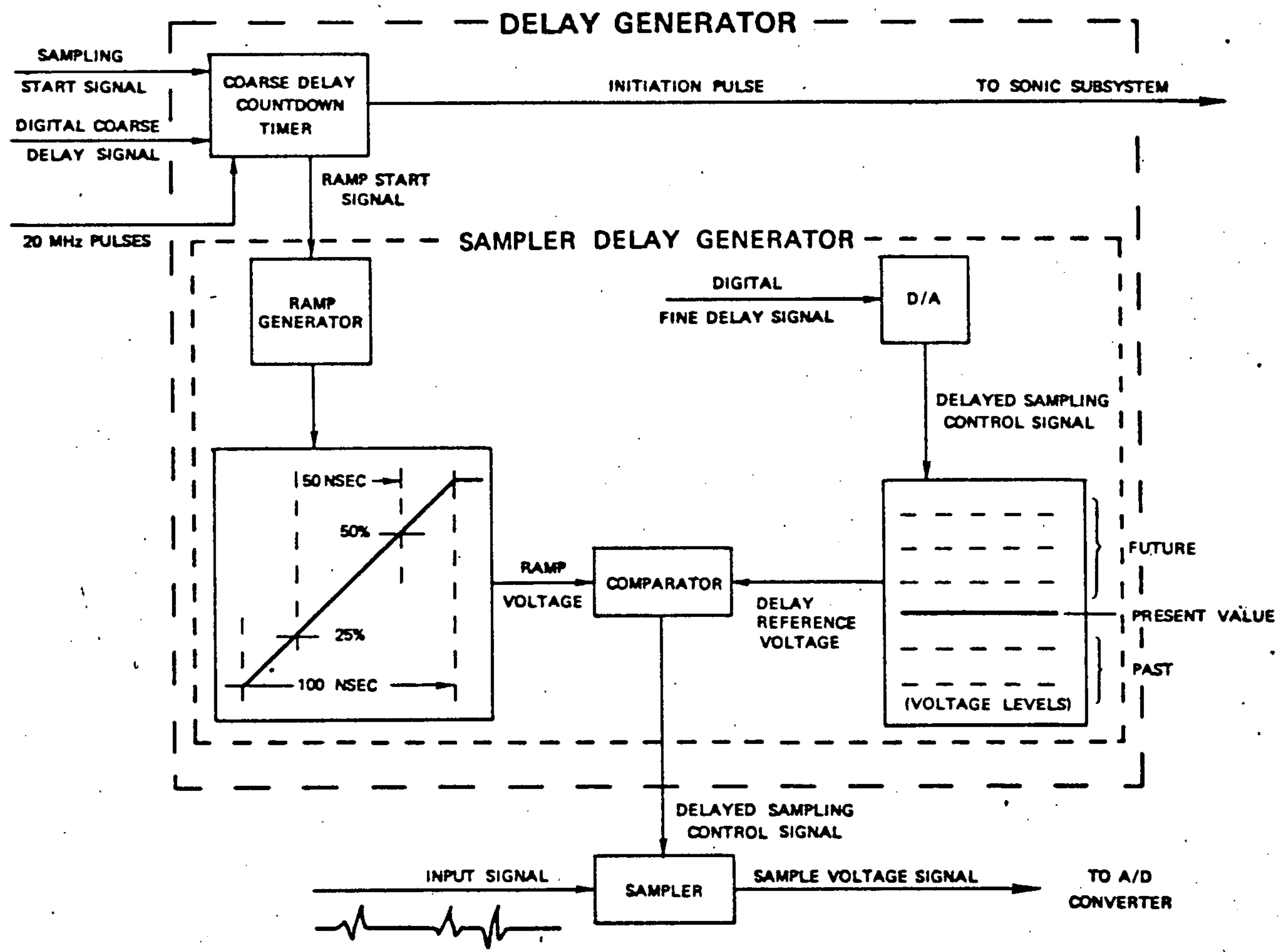


Fig 2b SAMPLING PATTERN for IDEALIZED ECHO

Fig. 3



DELAY GENERATOR
SAMPLING START SIGNAL
DIGITAL COARSE DELAY SIGNAL
20 MHz PULSES
COARSE DELAY COUNTDOWN TIMER
INITIATION PULSE
TO SONIC SUBSYSTEM
RAMP START SIGNAL
SAMPLER DELAY GENERATOR
RAMP GENERATOR
DIGITAL FINE DELAY SIGNAL
D/A
DELAYED SAMPLING CONTROL SIGNAL
50 NSEC
50%
25%
100 NSEC
RAMP VOLTAGE
COMPARATOR
DELAY REFERENCE VOLTAGE
FUTURE
PRESENT VALUE
PAST
(VOLTAGE LEVELS)
DELAYED SAMPLING CONTROL SIGNAL
INPUT SIGNAL
SAMPLER
SAMPLE VOLTAGE SIGNAL
TO A/D CONVERTER

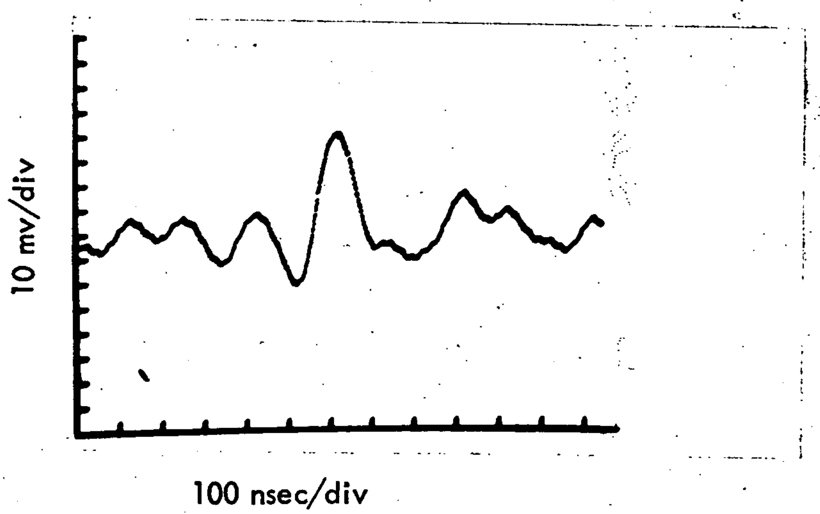


Fig 4a Original Echo

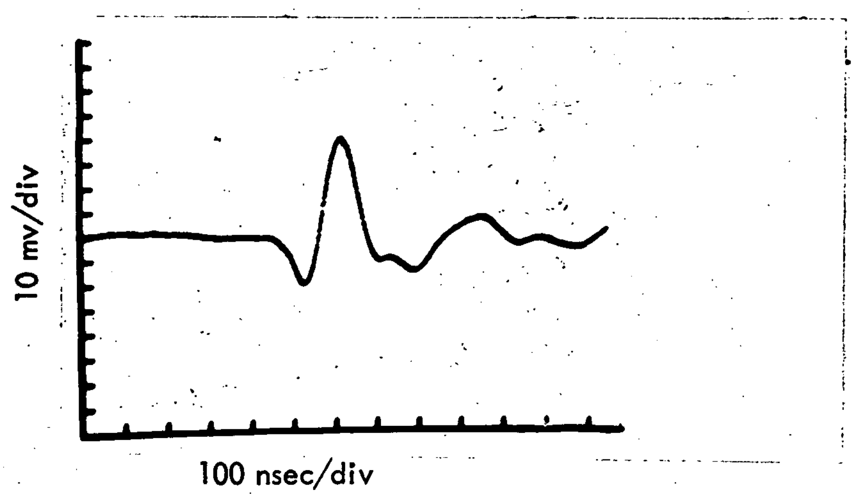


Fig 4b Differenced Echo

Data:
50 sweeps of
1000 points/sweep

1.25 nsec interval
per point

output attenuation
factor of 20

Fig 4 The DIFFERENCE PATTERN SHOWING the WELL DAMPED SONIC PULSE EMITTED by the TRANSDUCER

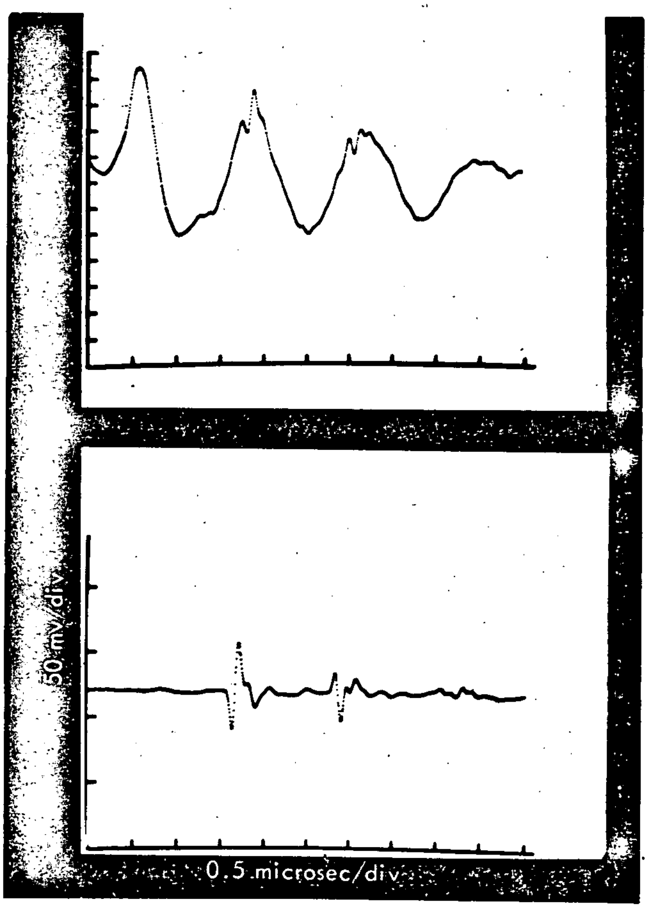


Fig 5 ECHO PATTERN from a LUCITE PLATE 1.67 mm THICK

C

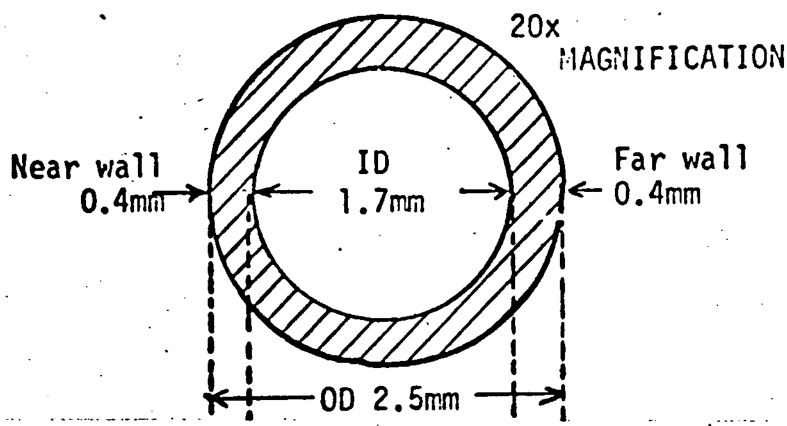
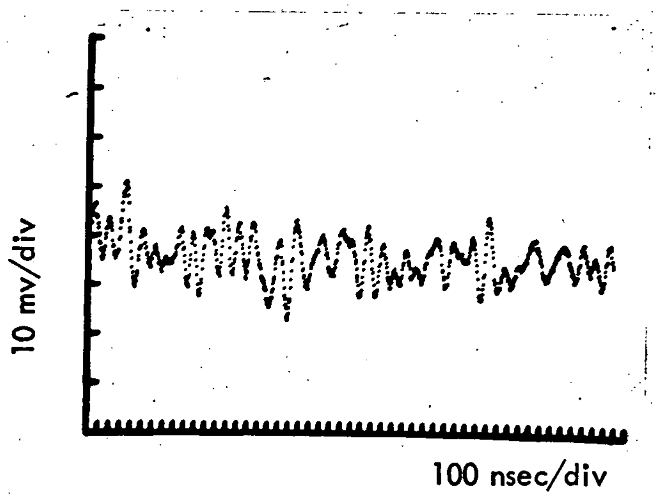


Fig 6 CROSS SECTION of PLASTIC TUBE SHOWING MECHANICAL MEASUREMENTS

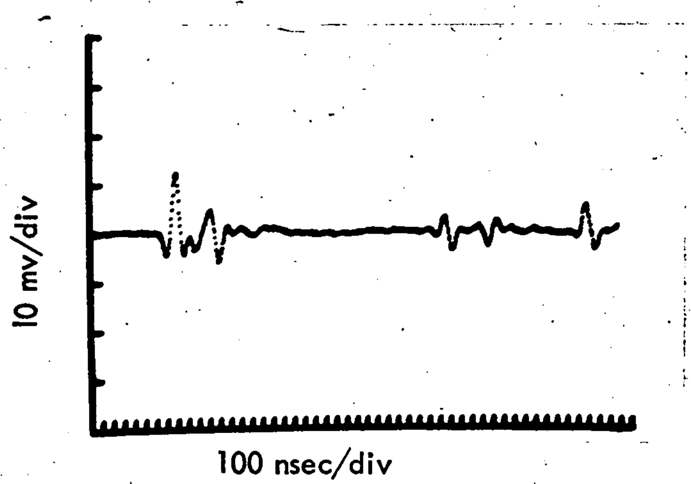


Data:
50 sweeps of
1000 points/sweep

5 nsec interval
per point

output attenuation
factor of 10

Fig 7 ORIGINAL ECHO from PLASTIC TUBE



Data:
50 sweeps of
1000 points/sweep

5 nsec interval
per point

output attenuation
factor of 10

Fig 8 The DIFFERENCE PATTERN SHOWING ECHOS from the FOUR SURFACES of the PLASTIC TUBE OF Fig 6

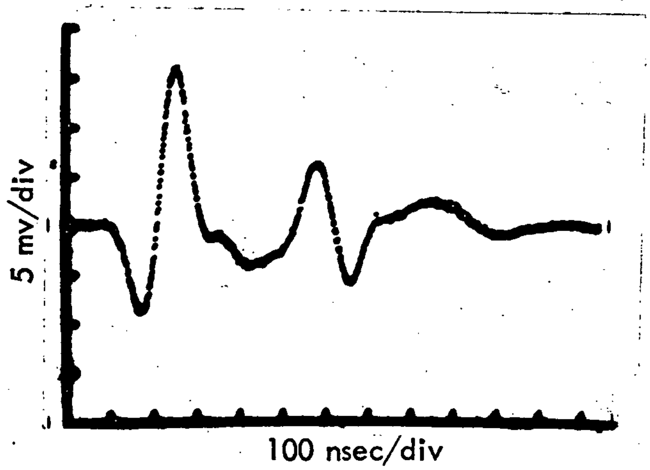


Fig 9a Near Wall

Data:
50 sweeps of
1000 points/sweep

1.25 nsec interval
per point

output attenuation
factor of 5

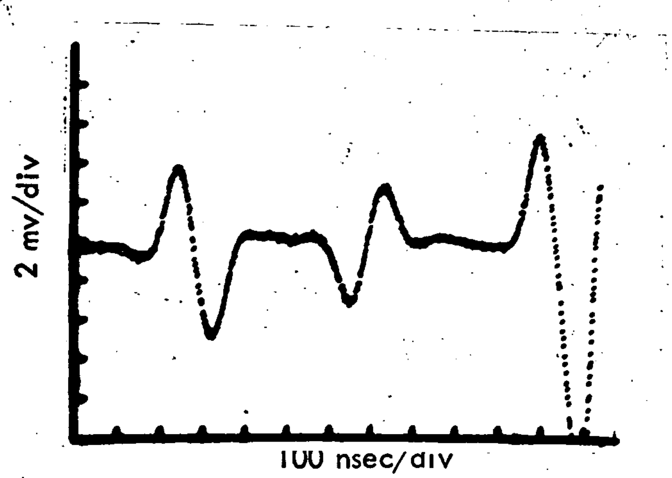


Fig 9b Far Wall

Data:
100 sweeps of
1000 points/sweep

1.25 nsec interval
per point

output attenuation
factor of 5

Fig 9 ECHO PATTERNS from the PLASTIC TUBE WALLS

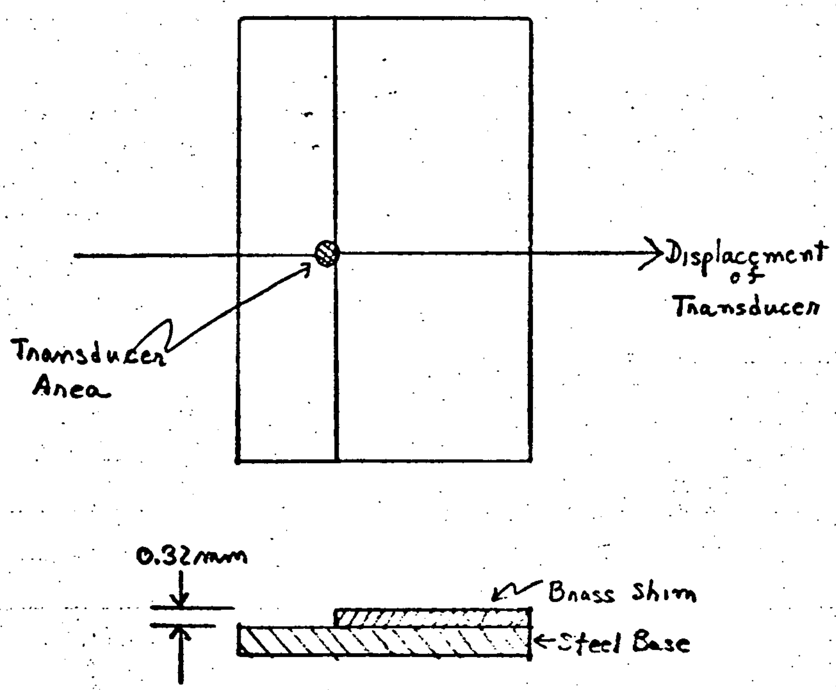
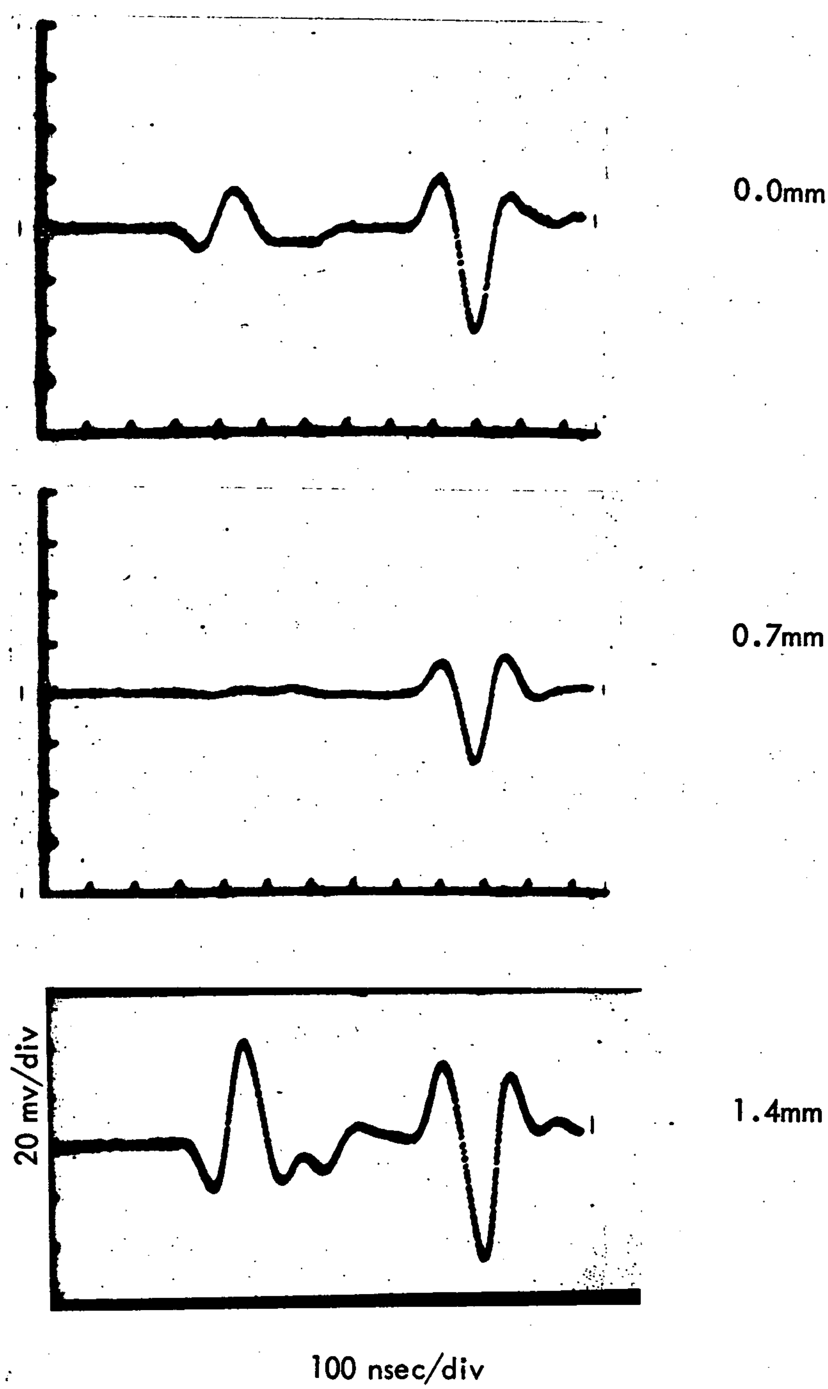


Fig 10 BRASS SHIM MOUNTED on STEEL PLATE



Data: 25 sweeps of 1000 points/sweep   1.25 nsec interval per point
output attenuation factor of 10

Fig 11 ECHOGRAMS from BRASS SHIM MOUNTED on STEEL PLATE

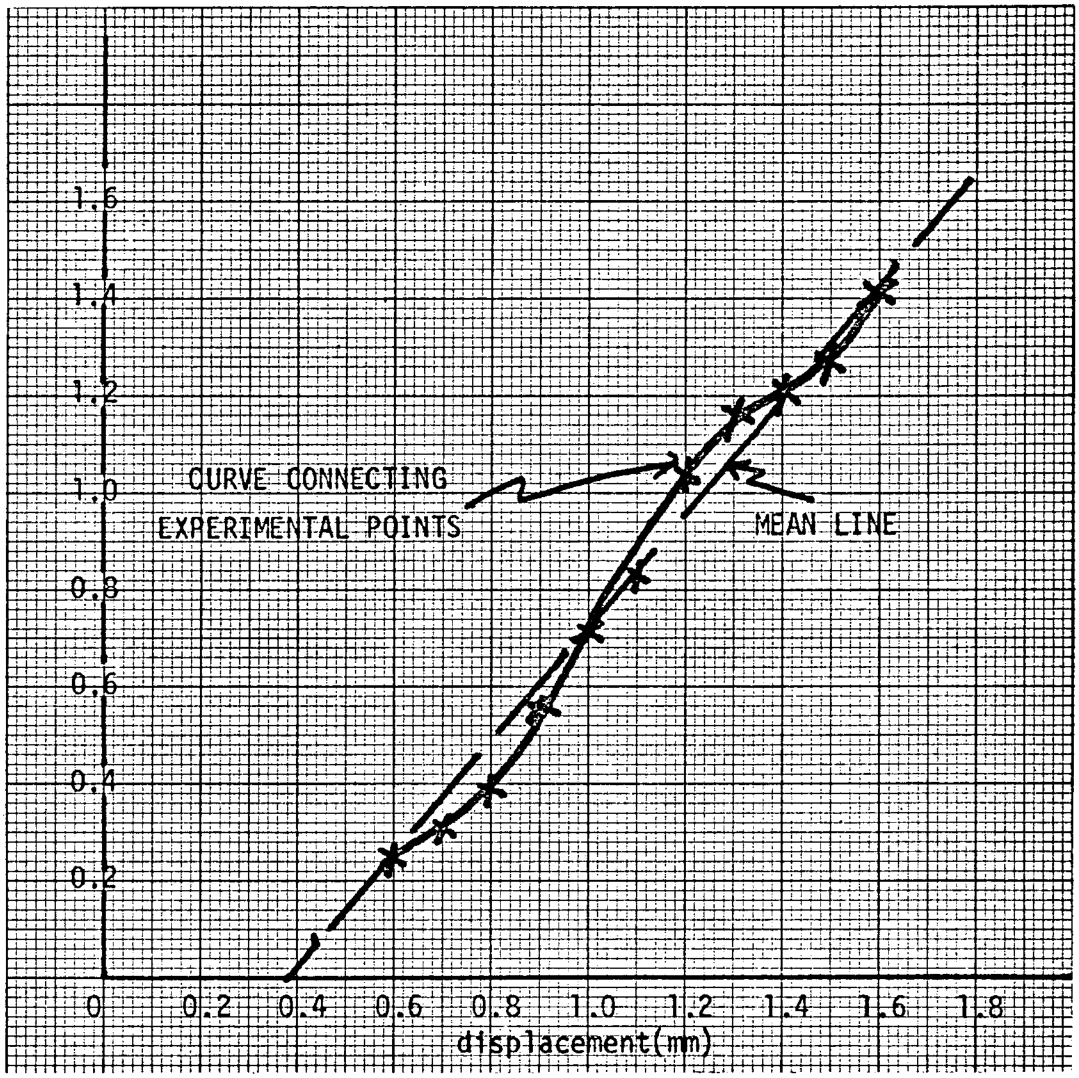


Fig 12 MAGNITUDE of BRASS ECHO as a FUNCTION OF DISPLACEMENT
(arbitrary magnitude units)